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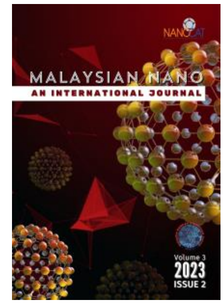

Review article

Nanotechnology in agriculture: A review of innovative utilization

Nur Balqis Zamri[a*] **and Mas Jaffri Masarudin**[a]

[a]*Department of Cell and Molecular Biology, Faculty of Biotechnology and Biomolecular Sciences, University Putra Malaysia, 43400 Serdang, Selangor, Malaysia*

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Corresponding authors:
nbalqiszamri@gmail.com

Abstract

The escalating challenges posed by swift population growth, global climate change, and occurrences of disease outbreaks to ensure food security necessitate innovate agricultural improvement techniques. In this intricate milieu, nanotechnology, with its remarkable advancements, emerges as a potent avenue for enhancing sustainable agricultural practices. This review underscores the current landscape of nanotechnology in agriculture, highlighting the classification and synthesis of nanomaterials. Furthermore, insightful applications of nano-based products in agriculture are meticulously elucidated in term of advantages and risks possessed. Notably, the regulatory frameworks from different countries have been addressed to ensure the safety of consumers and the environment. However, despite its myriad benefits, nanotechnology is not exempt from limitations and potential negative consequences, which are explored in the final section of this review.

Keywords: nanomaterials, agriculture, nano-based products, regulatory frameworks

1. Introduction

Over the preceding decades, scientists and agriculturists have been extensively discovering new solutions to amplify both crop quality and yield. With the onward march of technology, the potential arises to surmount the obstacles that currently limit sustainable and robust agriculture. Notably, in fields like nanotechnology, it presents an encouraging prospect for addressing numerous challenges confronting human society [1]. According to the Food and Agriculture Organization of the United Nations, there has been a significant rise in the proportion of individuals living below poverty threshold each year. Across the globe, approximately 800 million people are currently experiencing food scarcity due to the recent rapid population growth and stagnation in farming development [2]. This problem has led to an urgent to address this issue on a global scale as nearly one-tenth of the global population experienced moderate to severe food insecurity, which was most noticeable in Latin America and the Caribbean, with Africa and Asia following closely behind [3]. Moreover, it is estimated that global populace will reach 8.6 billion by the year 2030, with subsequent escalation to 9.8 billion by 2050 [4]. To address the requirements of this growing population, there must be an ongoing emphasis on food production while also preserving retaining natural ecosystems and their functions [5]. Previously a worldwide conference in 2009 has predicted that meeting the food demand for the global population in 2050 will necessitate a substantial increase in key commodities. For instance, meat production will need to grow from 200 million tons to a combined total of 470 million tons by 2050 [6]. Additionally, by the year 2020, global commercial pesticides usage reached up to 3.5 million tons, leading to soil and water contamination, residues remaining in crops, and eventually entering the food chain, thereby posing threats to human beings [7]. The worldwide proliferation of diverse diseases, drastic shifts in climate patterns, and the prevalence of mono-cropping; factors that render agricultural systems unsustainable, fragile, and less adaptable, further compound the issue [8].

In the pursuit of the goal to minimizing challenges, a target outlined among the United Nations' 17 sustainable development goals, nanotechnology emerges as a foremost solution. In retrospection, nanotechnology came to the forefront in the 1960s, a period ignited by the pioneering discourse of American Nobel Laureate Richard Feynman, who planted the seeds of nanoscience through his seminal talk [9] [10]. Since that pivotal breakthrough, nanotechnology has gradually yet profoundly revolutionized the agricultural sector, combatting undue reliance on chemical-based fertilizers by introduction of nano-agricultural products [11]. Consequently, agri-nanotechnology becomes imperative to enhance agricultural yield and delivering high-quality agricultural goods to humanity, all while mitigating adverse environmental impacts [12].

2. Nanomaterials

The term “nano” originates from the Greek word ‘nanos,’ which translates to “dwarf” or extremely small. Nanomaterials refer to particles that possess internal or external dimensions within the range of 1-100 nanometers (nm). Nanoscience involves the study of structures and molecules at sizes ranging from 1 to 100 nm, and the implementation of this knowledge in practical applications like devices is termed nanotechnology [13]. Typically, nanomaterials exhibit distinct or improved properties compared to their larger bulk counterparts [14]. Throughout study, various organizations and regulatory committees have put forth scientific definitions and explanations based on their comprehension. Due to the numerous origins of nanomaterials, their categorization has been condensed based on characteristics such as dimensionality, origin, composition, porosity, phases, and dispersion [15].

2.1 Classifications of Nanomaterials

Nanomaterials set themselves apart from larger-scale Earth materials by their dimensionality (size and morphology), which leads to four primary nanomaterial types (0D, 1D, 2D, and 3D). Nanomaterials with zero dimensions (0D), such as carbon quantum dots, fullerenes, magnetic nanoparticles, up conversion nanoparticles, graphene quantum dots, inorganic quantum dots, noble metal nanoparticles, and polymer nanoparticles, exhibit dimensions that are all within the nanometer scale (less than 100 nm) in each direction [16]. The supplementation of fullerene to the diet has shown to enhance the nutritional value of pigs in the field of livestock agriculture [17]. Nanomaterials that possess a one-dimensional structure (1D), including metals, metal oxides, and carbon-based variants like nanotubes, nanowires, and nanofibers characterized by a substantial aspect ratio, have a sole dimension exceeding 100 nm. In agriculture, carbon nanotubes are extensively employed to identify signaling molecules in plants during both abiotic and biotic stress situations. Their benefits include robust fluorescence stability, extended lifespan, and the ability to emit fluorescence within the mostly transparent near-infrared spectrum of living tissues. [18].

Nanomaterials of a two-dimensional nature (2D), such as silicate clays, black phosphorus, tin telluride nanosheets, graphitic carbon nitride, graphene, and transition metal dichalcogenides, exhibit two dimensions greater than 100 nm. These materials are characterized by their plate-like structures and consist of thin layers, with a minimum thickness of just a single atomic layer [19]. A study indicates that the utilization of graphene results in the acceleration of initial seed germination, a rise in root length, and the promotion of shoot growth in cotton seedlings [20]. Nanomaterials existing in a three-dimensional configuration (3D) possess dimensions exceeding

100 nm in all three directions. These encompass multi-nanolayers, bundles of nanowires, bulk powders, and dispersed nanoparticles. A recent instance of their utilization involves employing 3D nanostructured zinc oxide for sensing ammonia gas, applicable in scenarios such as poultry and agricultural fields [21].

When considering their source, nanomaterials can be classified into five distinct groupings: natural, incidental, bioinspired, engineered, and anthropogenic. Considering their origin, nanomaterials can be grouped into four categories: natural, incidental, bioinspired, engineered, and anthropogenic. Based on their chemical composition, nanomaterials are divided into carbon, inorganic, organic, and hybrid nanomaterials. As per the IUPAC naming convention, materials are placed within three primary categories determined by pore size: microporous, mesoporous, and macroporous structures. Additionally, nanomaterials can be categorized according to their level of crystallinity, falling into the classifications of crystalline, semi-crystalline (polycrystalline), or amorphous. Furthermore, nanomaterials can be organized as either dispersed or aggregated variations, contingent on their solubility and the nature of the solvent involved [22].

3. Synthesis methods of nanomaterials

Diverging from natural nanomaterials, engineered nanomaterials are meticulously synthesized within controlled laboratory or industrial settings. Consequently, their dimensions, form, and composition are adeptly manipulated. Numerous methodologies for synthesizing nanomaterials have been elucidated in research literature, each with its own categorization and attendant merits and demerits. The techniques employed to synthesize nanomaterials are typically divided into two categories: top-down and bottom-up approaches.

The top-down approach entails the transformation of bulk material into small nano-sized particles. While the simplicity of top-down methods is evident, they prove inadequate for manufacturing particles of irregularly shaped and extremely tiny particles. In essence, the difficulty in attaining requisite particle size and shape stands as the principal drawback of this strategy. Conversely, the bottom-up method is the opposite of top-down as this constructive technique synthesized nanomaterials with well-defined shape, size, and chemical constitution through growth and self-assembly of atoms and molecules as their building blocks [23]. Noteworthy top-down techniques encompass mechanical milling, laser ablation, etching, sputtering, and electro-explosion. Counterposed to this, bottom-up approaches include chemical vapor deposition, solvothermal and hydrothermal, sol-gel, soft and hard templating, and reverse micelle methods [24] [25].

4. Application of nanomaterial in agriculture

Nanotechnology is acknowledged as a hopeful path to tackle various agricultural obstacles. Its significance has risen markedly in recent years, giving rise to the development of nano-enabled products and inventive farming methods designed to elevate agricultural efficacy and efficiency [26]. This strategy introduces novel agronomic elements through nanofertilizers, nanopesticides, nanosensors, nanobiotechnology and nanozeolites [27].

i) Nanofertilizers for plant growth and crop yield

Nanofertilizers consist of plant nutrients enclosed within nanoparticles, with a minimum of 50% of the particles having a size smaller than 100 nanometers. Examples of nanomaterials used in crafting nanofertilizers include carbon nanotubes, graphene, and quantum dots [28]. Nanofertilizers represent a new breed of fertilizers that harness advanced nanotechnology to offer an effective and sustainable approach to fertilizing crops. Their design ensures a controlled release of plant nutrients, gradually disbursing them over an extended timeframe, thereby providing a steady and essential supply of elements to [29]. This controlled-release mechanism outperforms traditional fertilizers by reducing the necessity for frequent application and the quantity of fertilizer needed. With their elevated surface area-to-volume ratio, these nanomaterials are well-suited for both nutrient retention and release. Moreover, nanofertilizers have the capacity to curtail runoff and the leaching of nutrients into the surroundings, thus enhancing ecological sustainability. Additionally, they enhance the efficiency of fertilizer utilization, resulting in heightened crop yields and diminished overall expenses associated with fertilization. Especially in regions where conventional fertilizers prove inefficient or inadequate, nanofertilizers confer notable advantages [30]. By offering a more streamlined and cost-effective means of nourishing crops, nanofertilizers concurrently mitigate the ecological repercussions of fertilizer application. These innovations arise from a promising technological frontier that holds the potential to address escalating food demands and augment the sustainability of agriculture. However, it is crucial to acknowledge that nanofertilizers currently grapple with certain limitations, including elevated production costs and potential concerns regarding their impact on the environment and safety. Consequently, further investigation is imperative to gain a comprehensive understanding of their enduring effects on soil health, crop development, and the overall ecosystem [31].

ii) Nanopesticides for crop protection

Recent investigations have revealed that nano-pesticides have the potential to mitigate the harmful effects associated with conventional chemical pesticides. They offer a means of precise pest control and contribute to the development of intelligent nano-systems that address issues such as ecological imbalances and the adverse impacts on food security and crop yield [32]. Nano-pesticides demonstrate effectiveness over extended periods, addressing environmental concerns such as nutrient enrichment in aquatic systems and the accumulation of non-biodegradable substances within the food chain due to the controlled release of active ingredients. Additionally, nano-pesticides exhibit improved pest control capabilities due to the heightened solubility and stability of their active components [33]. However, there remains a need to refine these techniques to maximize their benefits for agriculture. Several key aspects pertaining to nano-scale pesticide delivery platforms have been discussed in a review. A vital key point revolves around the fact that the efficacy of nanopesticide development can be achieved through the adoption of green chemistry principles and environmentally sustainable practices. Furthermore, evaluating the practical utility of nanopesticides at the field level in comparison to traditional products is essential. Conducting environmental impact assessments is crucial for gauging the susceptibility of nanopesticides. Adapting policies for the application of nanomaterials in agriculture is also necessary [34]. The introduction of intelligent nanopesticides by agrochemical industries has the potential to offer various solutions, such as improved solubility, stability, controlled release, and targeted distribution of active components to specific organisms. Nonetheless, comprehensive research is imperative to comprehend the fate of nanopesticides within the environment. [35].

iii)Nanosensors for intelligent crop management

Nano-biosensors are pivotal in transforming agriculture through the innovation of diagnostic tools and methodologies. These sensors exhibit precision, efficiency, and affordability in addressing diverse concerns related to food, agriculture, and the environment. Notably, they find applications in agriculture by facilitating the detection of heavy metal ions, pollutants, microbial presence, pathogens, as well as swift monitoring of temperature, traceability, and humidity [36]. These nanosensors possess distinctive attributes that render them indispensable to the agricultural sector, including compact size, effectiveness, uniqueness, sensitivity, and reasonable cost [37].

In term of application, positioned on plant leaves, nanosensors capture hydrogen peroxide signaling waves. Inside leaves, plants employ hydrogen peroxide (H2O2) for communication, sending signals that trigger leaf cells to produce compounds that deter predators, such as insects, and facilitate repair. Nano-sensors encompass diverse nanoscale components like nanowires (for heightened sensitivity), carbon nanotubes (with extensive surface area), thin films, nanoparticles, and polymer-based nanomaterials. These sensors detect changes in conductance when semiconducting carbon nanotubes interact with specific chemicals. Consequently, nanosensors play a pivotal role in safeguarding crops and advancing the principles of sustainable agriculture. [38].

iv) Nanobiotechnology for genetic engineering and smart delivery systems

Enhancing crop yield, quality, and resilience to both abiotic and biotic stresses is a pivotal requirement for achieving sustainable agriculture through plant genetic engineering. Current methods such as Agrobacterium-mediated, biolistic bombardment, electroporation, and poly (ethylene glycol) (PEG)-mediated genetic transformation systems are widely employed. Nevertheless, these techniques come with drawbacks, encompassing species-specific limitations, tissue damage, suboptimal transformation rates, and high expenses [39].

In recent times, gene delivery methods based on nanotechnology have emerged as a promising avenue for plant genetic transformation. This nano-based approach exhibits remarkable transformation efficiency, favorable biocompatibility, effective shielding of exogenous genetic material, and the potential to facilitate plant regeneration [40]. However, the utilization of nanomaterials for gene delivery in plants is still at an early stage, and numerous challenges must be addressed before its widespread implementation [41].

v) Nanozeolites for soil enrichment

Zeolites find a wide range of applications in agriculture, particularly in soil management, water retention, and the removal of heavy metal pollutants. Their properties, such as ion exchange capacity and adsorption, hold significance in agronomy. Nano-zeolite implementation contributes to improved nutrient retention in soil and facilitates the gradual and sustained release of nutrients. They are also utilized as carriers or mediums for delivering nutrients, thereby enhancing nutrient utilization efficiency [42]. The growing interest in employing porous nano-zeolites in agriculture has been partially driven by concerns about the adverse effects of chemical fertilizers, which can lead to groundwater contamination. Unlike chemical fertilizers, zeolites are safe for human consumption and environmentally benign [43]. The favorable outcomes associated with zeolites encompass heightened crop productivity and growth, along with reduced greenhouse gas emissions and energy input. However, further research is essential to optimize the synthesis of hierarchical zeolites, assess their cost-effectiveness, and comprehensively understand their long-term effects on soil health and the agricultural ecosystem. [44].

5. Limitations of nanotechnology in agriculture

Nanotechnology has been praised as a groundbreaking advancement that spans numerous sectors, including agriculture, and offers both potential advantages and significant concerns. While the progress made in nanotechnology does present positive aspects, it is imperative not to overlook the potential negative outcomes. Nano-sized particles, which can be easily transported by air or water, bring about challenges related to containment and tend to accumulate within the environment. This accumulation affects soil, water, and air quality, thereby introducing ecological risks [45]. A particular cause for concern is the phenomenon of nano phytotoxicity, which is responsible for causing damage to plants and ecosystems due to the release of toxic nanomaterials. The presence of nanoparticles disrupts the balance of microorganisms in the soil, resulting in reduced fertility. Moreover, these nanoparticles can accumulate in plants and animals, thereby influencing their overall well-being. The harmful effects include structural damage, oxidative stress, and disruptions in reproductive processes in plants [46]. The severity of phytotoxicity is influenced by factors such as particle size, concentration, and the condition of the soil. Smaller nanoparticles tend to cause more pronounced harm. The exploration of effects occurring within plant cells requires further investigation [47].

In addition, the impact of nanotechnology extends to the environment in a detrimental manner. Nanoparticles are released into the atmosphere, leading to consequences for soil, air, water, and living components. These nanoparticles have a bearing on the regulation of atmospheric temperatures and water systems, and they can also transfer through the food chain, ultimately affecting various organisms and subsequent generations. While research on the transfer of nanoparticles through the food chain remains limited, certain examples highlight instances of transfer from algae to invertebrates and from daphnia to fish. Detrimental effects are not confined to the realm of plants and animals alone. Nano-based pesticides, for instance, negatively impact crucial pollinators such as bees. Soil microflora also suffer as a result of exposure to nanoparticles, leading to repercussions on decomposition processes and soil quality. These effects are guided by the specific characteristics of nanoparticles and the duration of exposure [48].

The implementation of nanotechnology in agriculture raises concerns about human health. Such concerns encompass respiratory, cardiovascular, and neurological issues resulting from exposure to nanoparticles. Workers involved in the production of nanomaterials are at an elevated risk of health problems. The financial demands associated with investing in nanotechnology for agriculture could potentially exclude small-scale farmers, thus further exacerbating existing inequalities [49]. Ethical considerations emerge in the context of food safety and the creation of genetically modified organisms (GMOs). Worries revolve around the potential health risks linked to the presence of nanomaterials in food, compounded by the lack of comprehensive long-term research on the effects of nanoparticle exposure. The creation of GMOs through nanotechnology also triggers ethical discussions. Humans are not immune to the risks associated with nanoparticles. Despite the benefits that nanotechnology offers to the field of agriculture, it is essential not to overlook the potential adverse health effects on humans. The consumption of nanoparticle-exposed produce or packaged foods could lead to damage to organs, DNA, and cellular structures. Given the limited understanding of interactions between nanoparticles and cells, it is imperative to engage in research aimed at developing strategies to mitigate and manage the harm caused by nanoparticles to ecosystems, including microorganisms and human health [50].

6. Policies and regulatory frameworks for nanomaterial-based agricultural products

The integration of nanotechnology into the agricultural sector required careful assessment before societal acceptance. The potential advantages and associated risks must be balanced, considering environmental, health, social, ethical, and economic factors. Therefore, the implementation of a regulatory framework becomes essential to oversee the safety standards of nanotechnology in the various domains. Public opinion plays a crucial role in bolstering the nano-agricultural sector.

Regulatory agencies worldwide, such as the European Union Scientific Committees and Agencies (EUSCA), Joint FAO/WHO Meeting on Pesticide Residues (JMPR), and the United States Food and Drug Administration (USFDA), are responsible for providing guidelines and formulating policies and regulatory frameworks for the secure utilization of nanoproducts. For example, in the US, the USFDA has approved nano additives, packing materials, and supplements for safe commercial use. The California Department of Toxic Substances Control mandates disclosure of relevant details about nanomaterials in chemicals. While the FDA regulates products rather than technologies, the UK's Institute of Food Science and Technology emphasizes pre-market testing of nanoproducts [51].

In the European Union, the REACH (Registration, Evaluation, Authorisation, and Restriction of Chemicals) authority oversees the application of nanomaterials in the agri-food sector. Various European Commission regulations address safety standards and risk management in agro nanotechnology. For instance, Food Law Regulation, Food Additives Regulation, and Pesticides Directive offer guidance on agrochemicals and nanomaterials.

Different countries have distinct regulatory approaches. China, through the Ministry of Science and Technology (MOST), focuses on standardizing protocols for nanotechnology. Australia's Australian Pesticides and Veterinary Medicines Authority and Food Standards Australia New

Zealand oversee agri-food production. In India, although specific policies for nanoproducts are lacking, the Department of Science and Technology (DST) and Ministry of Environment and Forests and Climate Change (MOEFCC) address concerns related to nanotechnology. China's Ministry of Agriculture and Rural Affairs (MARA) regulates genetically modified organisms, and the Therapeutic Goods Administration (TGA) in Australia classifies nanosilver-based medical equipment as class III medical devices [52].

Regulation involves not only governmental agencies but also non-state actors like non-governmental organizations (NGOs), industrial associations, and academic institutions. The global private organization ISO proposes standards for the manufacture and toxicity assessment of nano-based products, contributing to hybrid regulation. The collaboration between scientists, civil society groups, and regulating bodies influences the development of policies. Strategies such as self-regulation, co-regulation, and meta-regulation are gaining recognition in the nano-agri sector. Self-regulation involves private agencies assessing their practices, co-regulation entails collaboration between state and industry, and meta-regulation regulates the regulators themselves. Such efforts collectively contribute to the responsible and sustainable use of nanotechnology in agriculture [53].

7. Conclusions

Nanotechnology carries significant potential for revolutionizing the agricultural sectors through the ongoing advancement of nano-enabled products and innovations. Nevertheless, challenges concerning safety, environmental impact, regulation, and public acceptance demand attention. Emphasizing environmentally conscious approaches such as green chemistry and utilizing nanomaterials that are synthesized and inspired by biological processes can provide sustainable solutions. Establishing robust regulatory frameworks, enhancing public awareness and engagement, and conducting comprehensive risk assessments are imperative to fully harness the potential of nanotechnology while upholding safety for both the public and the environment. Ultimately, the substantial promise of nanotechnology in agriculture requires a careful and responsible approach.

Conflicts of interest

The authors declare no conflict of interest.

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